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BEFORE THE
PUBLIC SERVICE COMMISSION OF WISCONSIN

Application of Highland Wind Farm, LLC, for a Certificate of Public Convenience and Necessity To Construct a 102.5 Megawatt Wind Electric Generation Facility and Associated Electric Facilities, to be Located In the Towns of Forest and Cylon, St. Croix County, Wisconsin

Docket No. 2535-CE-100

Ex.-CW-Cook-7

Please enter the attached exhibit, Ex.-CW-Cook-7, *Wind turbine sound pressure level calculations at dwellings,* by Keith, et al. J. Acoust. Soc. Am. 139 (3), March 2016.

Wind turbine sound pressure level calculations at dwellings

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This paper provides calculations of outdoor sound pressure levels (SPLs) at dwellings for 10 wind turbine models, to support Health Canada's *Community Noise and Health Study*. Manufacturer supplied and measured wind turbine sound power levels were used to calculate outdoor SPL at 1238 dwellings using ISO [(1996). ISO 9613-2−Acoustics] and a Swedish noise propagation method. Both methods yielded statistically equivalent results. The A- and C-weighted results were highly correlated over the 1238 dwellings (Pearson's linear correlation coefficient $r > 0.8$). Calculated wind turbine SPLs were compared to ambient SPLs from other sources, estimated using guidance documents from the United States and Alberta, Canada. © *2016 Crown in Right of Canada. All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).*
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I. INTRODUCTION

In Canada, the sound pressure level (SPL) of outdoor community noise at a dwelling is typically predicted with the International Organization for Standardization standards (ISO, 1993, 1996). Wind turbine noise (WTN) can be difficult to distinguish from ambient sound (Pedersen and Halmstad, 2003; Van Renterghem *et al.*, 2013) and varies with weather conditions. As a result, calculations can be more representative of long-term levels than estimates based solely on measurements (ISO, 2007). It is not currently feasible to use more sophisticated methods than ISO (1996) as those methods require data that are usually not available: a sound speed profile, or wind speed and temperature as a function of height (Attenborough *et al.*, 1995). The derivation of such data using cloud cover (Eurasto, 2006; Jonasson, 2007) is also not feasible in rural Canada as this information is typically only available in urban areas or at airports, which often are hundreds of kilometers away, and are not typically near wind turbines.

The ISO (1996) noise propagation standard was not developed for high (>30 m) noise sources such as wind turbines, and its accuracy for distances over 1 km is not specified. As a result, several studies have investigated the agreement between calculated and measured SPL from wind turbines, usually for favorable (downwind) conditions. At distances up to 2 km downwind of the turbines, calculated SPLs were found to underestimate the measured SPLs by 0−5 dB (van den Berg, 2004; Forssén *et al.*, 2010; Plovsing and Søndergaard, 2011; Öhlund and Larsson, 2015).

When modeling wind turbine SPL there are a number of considerations that can increase the modeled values to offset possible underestimates in SPL. In the context of WTN exposure and health, the reference period of time used in the *Community Noise and Health Study* (CNHS) questionnaire

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required an estimate of long-term exposures (Michaud *et al.*, 2016). Ontario (ON) and British Columbia (BC) perform calculations with an assumed temperature of 10 °C and at a relative humidity of 70% (ONMOE, 2008; BC, 2012). These are plausible conditions where the atmospheric absorption is near its minimum (ISO, 1993). In addition, in these provinces, all farm fields are assumed to be mixed ground, 70% absorbing and 30% reflecting, where the reflective part can increase the calculated A-weighted SPL by 1 dB at 4 m receiver height (per ISO, 1996). Higher receiver heights tend to increase SPL due to reduced ground absorption effects, and second or higher storey heights can be used in assessments. The provinces also use the maximum wind turbine sound power for sound level monitoring.

Over a period of a year, changing meteorological conditions can make the long-term average SPL as much as 2 dB lower than the short-term SPL under favorable conditions (ISO, 1996). Research by van den Berg (2008) has shown that for the weather conditions in the Netherlands (for two turbine models), 4.7 dB (standard deviation, SD = ±1.5 dB) must be added to the sound power levels corresponding to 8 m/s wind speed to calculate the long-term average A-weighted DENL (day evening night equivalent SPL). The long-term yearly averaged SPL (van den Berg, 2008) was similar in each of the day, evening and nighttime periods so that the DENL and DNL (day night equivalent SPL; USEPA, 1974) would be approximately equal. For a truly constant SPL, DENL, and DNL are both 6.4 dB higher than the equivalent constant SPL. As such, the yearly average DENL for a wind turbine in the Netherlands would be approximately 1.7 dB (SD = 1.5 dB) lower than the DENL calculated for a constant 8 m/s wind speed. A similar difference applies to DNL or yearly averaged SPL.

There is no current modeling procedure to account for short-term, site-specific variations in sound propagation or sound characteristics (e.g., tonal noise, impulsive noises or amplitude modulation) that could affect an individual's response. This evaluation would require statistical data relevant to the terrain, weather and wind turbine models, as well as a more thorough, quantitative knowledge of the sound characteristics. As such, short-term, site-specific variations are outside the scope of the CNHS and, if present, would be more suited to a case-by-case analysis.

This paper describes the calculation of SPLs and noise propagation modeling carried out for the CNHS. The C-weighted SPLs are estimated and compared to outdoor A-weighted SPLs to evaluate the potential for low frequency noise issues at the selected wind turbine and dwelling locations. Finally, the ambient SPLs in the study areas are estimated for comparison to WTN SPLs.

II. METHODS

A. Study area description

Outdoor SPLs were calculated at 1238 dwellings in the vicinity of 399 wind turbines with rated electrical power output ranging from 660 kW to 3 MW. The distribution of the number of wind turbines is as follows: 16 at 0.66 MW rated electrical power, 52 at 1.5 MW, 24 at 1.65 MW, 82 at 1.8 MW, 30 at 2 MW, 187 at 2.3 MW, and 8 at 3 MW. All turbines were of modern design with tubular towers and 3 pitch-controlled rotor blades upwind of the tower. The average rated electrical power output was 2.0 MW with 0.4 MW SD. There were 315 wind turbines in southwestern Ontario and 84 in Prince Edward Island (PEI). Most wind turbines had a hub height of 80 m, and rotor diameter of approximately 80 m. All dwelling locations were on generally flat agricultural land with crops ranging from soybeans to mature corn stalks. Between many fields there were deciduous, and/or coniferous treed wind breaks as well as scattered small forested sections. In these areas, tree heights range from 10 m to a maximum of 30 m (Gaudet and Profitt, 1958; Sharma and Parton, 2007; Ontario Ministry of Natural Resources, 2014). Roadways varied from gravel to two lane asphalt highways, as well as a single six-lane concrete surface freeway in ON. Most roads were within agricultural zones, averaging less than 1000 vehicles daily (ONMT, 2010). There were 34% of the dwellings associated with built up areas (i.e., in towns, or along roads with population density above 1740 people per square mile) and 38% had a population density below 300 people per square mile (Statistics Canada, 2011).

B. Calculated outdoor A-weighted SPLs at dwellings

Consistent with standard Canadian practice, outdoor WTN SPLs were modeled at dwellings using the ISO 9613 standards (ISO, 1993, 1996). A simpler Swedish method (SEPA, 2012) was also used for comparison. The Swedish method included all turbines in the CNHS, and the ISO (1996) calculations were limited to wind turbines within a radius of 10 km of dwellings. Calculations were based on manufacturer supplied octave band sound power spectra for a wind speed standardized to 8 m/s at 10 m height as per the International Electrotechnical Commission (IEC, 2012) standard. Consistent with common practice in Canada (ONMOE, 2008, 2011; BC, 2012) temperature was set to 10 °C, relative humidity to 70%, mixed ground (i.e., 70% absorbing and 30% reflecting), and a receiver height of 4 m.

Locations of wind turbines and dwellings were estimated using global positioning system (GPS) data. The wind turbine GPS data were obtained from wind turbine operators and were compared with an Aeronautical Obstacle database licensed from Canada's civil air navigation service (NAV Canada). GPS positions of participating dwellings were obtained by Statistics Canada during their in-person survey and these were compared with topographic maps (GeoBase, 2010a). If the comparison of GPS data sources showed positional differences of more than 40 m, the positions were corrected using Google Earth, Google Street View, Bing Maps, and in consultation with the GPS data providers.

Calculations based on the ISO (1996) sound propagation standard were made with CadnaA version 4.4 software (DataKustik GmbH®, 2014). Additional calculations with this software were performed using the Harmonoise module (as implemented by DataKustik GmbH®, 2014). Forested areas, hydrological features and 1 m contour interval elevation data were obtained from GeoBase (2005, 2010a), and were processed using Global Mapper v.14 software (Blue Marble Geographics®, 2014). Buildings were not included in model

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calculations for two reasons. One reason was that the building heights and locations were only sometimes known. Second, the scale of spatial variations in dwelling SPL, due to building reflection and shielding is less than the 40 m position accuracy for dwellings.

Calculations for SPLs based on the Swedish noise propagation method (SEPA, 2012) used Microsoft Excel software. For the turbines in the study (Keith *et al.*, 2016) the chosen wind speed, 8 m/s, approximated the speed at which the sound power levels were near maximum and independent of wind speed, so the "*k*" factor from the Swedish method was set equal to zero.

C. Calculated outdoor C-weighted SPLs at dwellings

C-weighted levels were calculated by extending ISO (1993, 1996) to lower frequencies. The propagation calculations at 16 and 31.5 Hz were assumed to have the same change with distance as at 63 Hz. At these low frequencies farm fields are acoustically reflecting with negligible atmospheric attenuation (Sutherland and Bass, 2004, 2006). The CNHS locations also had negligible barriers to sound, and no intervening large bodies of water. At and above 63 Hz, both the A- and C-weighted SPL modeling used the same octave band data from manufacturers. As manufacturers did not provide 16 and 31.5 Hz octave band sound power levels, measured data (Keith *et al.*, 2016) were used in these octave bands for the modeling. At all frequencies the measured 1/3 octave band data were also used to identify, and correct for, significant discrete frequency components that could affect the conversion from the A- to C-weighted data.

D. Calculated yearly averaged SPL at dwellings using wind turbine operational data

Using an analysis similar to van den Berg (2008), the difference between the SPL calculated at 8 m/s wind speed and the yearly averaged daytime, evening and nighttime SPL was also calculated. This was based on the wind turbine nacelle anemometer data obtained in the 12 months before May 2013 (immediately preceding the CNHS). The data were averaged in 10 min intervals and combined with the manufacturers' sound power levels as a function of wind speed. Wind speed and sufficient sound power data were available for four of 10 wind turbine models, in eight of 14 wind turbine facilities. Using the corrections found for this data, an averaged correction was applied to all wind turbines.

E. Estimation of ambient noise SPL in the absence of WTN

The A-weighted ambient SPLs at dwellings, based on population density and transportation, were estimated using the noise guidance from Alberta, Canada (DeGagne, 1999; AUC, 2013) shown in Table I. This table provides estimates of ambient noise including all natural and manmade sources, with the exception of those produced by the energy industry. At some locations it is possible to have a very low ambient SPL and the AUC (2013) guidance provides for adjustments of up to ±10 dB when unusually low (or unusually high) SPLs are documented by measurements.

The AUC (2013) guidance is based on distance to roads that have more than 90 vehicles per night in any month. This value, assuming 10% of the traffic volume occurs at night, approximates the threshold for reported data from ON and PEI (ONMT, 2010, 2013; PEIMT, 2012). Geospatial data for road and rail (GeoBase, 2010a,b, 2012) was processed with the Global Mapper v. 14 software and the dwelling density was adjusted (typically increased by 10%) to conform to the most recent Statistics Canada census (Statistics Canada, 2012).

For ON dwellings near the 6 lane freeway, nighttime SPLs were estimated using the US Traffic Noise Model (FHWA, 1998) and CadnaA software (DataKustik GmbH®, 2014). A speed of 105 km per hour was used for heavy trucks as this value is controlled by a speed limiter (Ontario Highway Traffic Act, 2011). For cars, not a dominant noise source, a speed of 120 km per hour was used as a reasonable worst case. A concrete road surface was used with 78% of the traffic volume during the day, and 10% of that daytime traffic made up of heavy trucks. The evening was assumed to have 10.8% of the traffic volume of which 15% was assumed to be heavy trucks. Heavy trucks were assumed to make up one quarter of the nighttime traffic volume. As actual values were not known, Austrian values were used as implemented by DataKustik GmbH® (2014).

The AUC (2013) predictions were compared to the available short-term measurements at eight dwellings in the CNHS area, where dwelling wall transmission loss was evaluated. These homes did not participate in the survey portion of the CNHS. Attended ambient noise measurements were available from measurements according to ISO (1998), and made 2 m from the dwelling facade at a height of 1.5 m above the bedroom floor. With the possible (unavoidable)

TABLE I. AUC (2013) estimates of average overall A-weighted nighttime ambient SPL. Population density in persons per square kilometer (km) was derived from the specified dwelling density per quarter section (where quarter section is interpreted as an area with 454 m radius) assuming 2.9 persons per Canadian farm dwelling (Statistics Canada, 2011). To convert to either DNL or daytime SPL add 10 dB to the levels in the table.

		Population density, persons per square km		
		<40	40 to 720	>720
Distance to transportation, (road or rail)	<30 m	45 dB	48 dB	51 dB
	30 to 500 m	40 dB	43 dB	46 dB
	>500 m	35 dB	38 dB	41 dB
		Number of dwellings in CNHS (% of total in brackets)		
		100 (8%)	1106 (89%)	32 (2.6%)

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exception of distances to building edges, these measurements were consistent with the ISO (2007) procedures for a +3 dB microphone position in front of a facade. The measurements were only made when there were no passing cars and no activity from nearby noise sources. At each location, the measurement was corrected by (i) subtracting, (arithmetically), 3 dB for the facade reflection (ISO, 2007) and (ii) subtracting (on an energy basis), the calculated WTN SPL. This yielded a lower bound on the ambient noise level at the time of the measurement.

F. Accuracy of modeling results

Uncertainties in the ISO (1996) and Swedish (SEPA, 2012) calculation methods are expected to have a SD of approximately 4 dB for distances less than 1 km. This is based on the 3 dB SD given in the ISO (1996) method, the SD for the wind turbine sound power level of 2 dB (Keith *et al.*, 2016) and the comparatively small additional uncertainty from GPS position data (SD $\leq$1 dB).

At the greatest distance of 10 km in the CNHS the standard deviation may approach 10 dB. This is due to the range of values that can occur at larger distances. The ISO (1996) standard assumes spherical propagation with 6 dB reduction per doubling of distance. At distances beyond 10 times the source height weather conditions have a stronger influence (ISO, 2007) and an acoustic shadow can occur. Conversely, beyond approximately 1 km under favorable propagation conditions, up to a frequency of 70 Hz (MG Acoustics, 2014), WTN can propagate cylindrically at 3 dB per doubling of distance (Willshire and Zorumski, 1987; Hubbard and Shepherd, 1991; MG Acoustics, 2014).

The C-weighted results were assumed to have a slightly larger uncertainty than the A-weighted results due to additional uncertainties in the measurements below 63 Hz (Keith *et al.*, 2016). As such the C-weighted values were assumed have a 5 dB SD within 1 km of the wind turbines, rising to 12 dB at distances of 10 km.

The Alberta predictions (AUC, 2013) are estimated to have an uncertainty of 6 dB SD. This is based on Schomer *et al.* (2011) who estimated a SD ranging from 4.5 to 5.2 dB for similar data at a predominantly higher population density and noted that there is more scatter to the data at a lower population density.

G. Measured outdoor SPL at a dwelling

In one case, propagation modeling was compared to measurements at a dwelling located 290 m from the closest wind turbine in a wind turbine facility. Based on weather data from wind turbine anemometers and a local ground based weather station (Keith *et al.*, 2016), 10 s SPL measurements were collected at a microphone flush with the ground (per IEC, 2012) when the wind speed at the turbine nacelle was 7.5−8.5 m/s. At 63 Hz the ISO (1996) propagation standard treats the ground as hard and always adds 3 dB to the modeled levels. Above 63 Hz, assuming mixed ground (30% hard and 70% soft), ISO (1996) adds up to 1.1 dB to the modeled levels due to ground reflection (this value may be lower depending on receiver height or distance from the wind turbine). As a result, to account for reflection in the ground level measurements, they were corrected by subtracting 3 dB at 63 Hz and below, and by subtracting 6 dB at higher frequencies so as to compare to the modeled levels at 4 m height (which approximates a free field).

III. RESULTS AND DISCUSSION

A. Swedish method versus ISO standard at 8 m/s wind speed

The ISO (1996) noise propagation method and the simpler Swedish method (SEPA, 2012) have a similar theoretical basis, so comparison of the results was not made to validate the propagation model. Rather, comparison of the results acts primarily as a check on the consistency of the calculation procedures. Statistically there was little difference between the results obtained with either method. For A-weighted SPLs greater than 25 dB, the Swedish method yielded slightly higher values, with differences ranging from −0.2 to 2.7 dB, and an average difference of 1.1 dB (Pearson's linear correlation coefficient $r > 0.99$). Differences became more pronounced beyond 1 km distance as compared to the ISO (1996) propagation standard because the Swedish method uses slightly lower air absorption and omits ground absorption, and (as calculated for the CNHS) included wind turbines at distances larger than 10 km. These findings provide an independent check of the ISO (1996) calculations. The consistency in the results within their respective SDs also suggests that, using the ISO (1996) model, there is little effect of ignoring turbines beyond 10 km. The agreement between the two methods also shows that over flat farmland, SEPA (2012) can be a useful alternative to ISO (1996). Furthermore, these results show that the CNHS SPL estimates were calculated in a manner that is similar to, or consistent with, a range of previous studies (Pedersen and Persson Waye, 2004; Pedersen, 2007; Pedersen *et al.*, 2009; Pawlaczyk-Łuszczyńska *et al.*, 2014). Note, however, that Pedersen and Persson Waye (2004) and Pedersen (2007) used an older version of the Swedish method (SEPA, 2001) which underestimates SPL beyond 1 km (below about 35 dB A-weighted, depending on the wind turbine characteristics).

B. Comparison of calculated and measured outdoor SPL at a dwelling

Figure 1 shows a comparison of modeling with 2.5 h of measured data (at 0 m, i.e., ground level) obtained near one dwelling when the wind was 8 m/s from the direction of the nearest wind turbine. The ISO (1996) modeling was done at both 0 m receptor height and at the 4 m receptor height used for the CNHS. While agreement between all curves is good below 125 Hz, the measurements and calculations clearly separate at 2 and 4 kHz where measured levels were influenced by audible wind-induced noise from a dry corn field and some trees within 30 m of the microphone position.

At 500 Hz, there appears to be a point of inflection in the measured curve where the ISO (1996) sound propagation standard would predict a notch due to ground absorption. Close to a wind turbine ISO (1996) may overestimate ground

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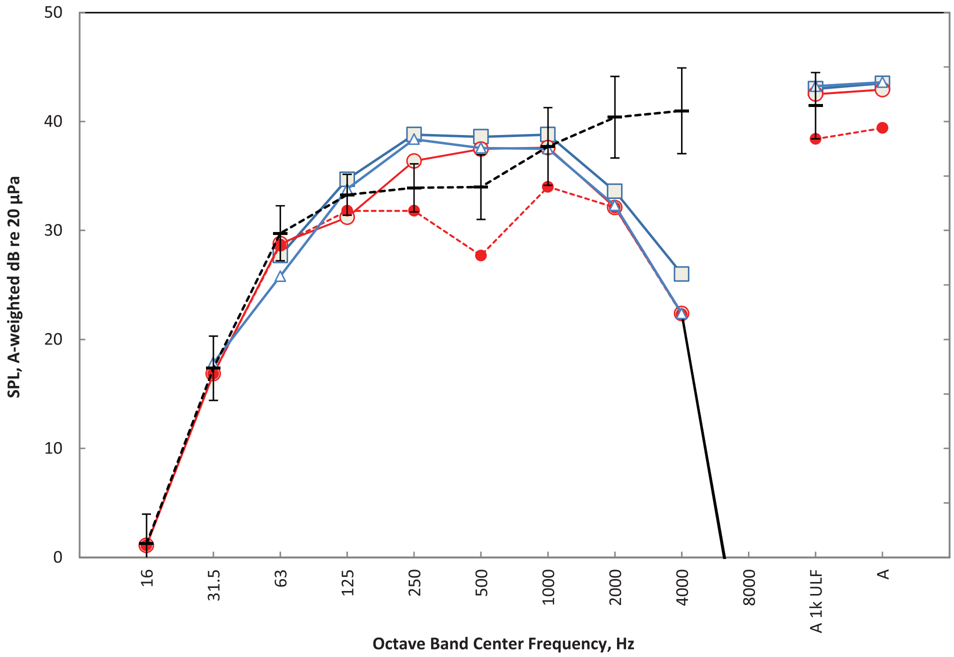

FIG. 1. Comparison of measured and modeled A-weighted SPL at a position 290 m from a wind turbine in a wind turbine facility. On the right hand side are shown the A weighted overall SPL and A-weighted overall SPL with an upper limiting frequency (ULF) of 1 kHz. Black bars and dashed black line: measured energy average SPL at 0 m receptor height with 1 SD error bars; open squares: Swedish method; open triangles: Harmonoise SPL at 4 m height; open red circles and red dashed line: ISO (1996) at 4 m height; filled red circles: ISO (1996) at 0 m height.

attenuation when the receptor height is close to the ground. In such a case, the ISO (1996) standard assumes similar ground absorption for all sources more than 3.5 m high. Conversely, for a receptor height above 3.5 m, the ISO (1996) standard predicts little ground absorption. Wind turbines are high sources, and these measurements were located within 2 km of a large body of water. Therefore, the simple models used may not adequately reflect short term measurement results.

For comparison, the Harmonoise model closely matched the Swedish method and ISO (1996) results at 4 m height. Notably, the A-weighted results from the Harmonoise model varied within a 0.3 dB range for all possible combinations of measurement height (0 or 4 m), wind direction, time of day and atmospheric stability.

C. Calculated outdoor A-weighted SPLs at dwellings using wind turbine operational data

Calculated sound power levels using wind speed from the wind turbine nacelle anemometers and the manufacturers' sound power levels showed that for wind turbines in the CNHS areas, the yearly average sound power level, is approximately 4.5 dB lower compared to continuous wind turbine operation at 8 m/s wind speed. Day, evening, and nighttime yearly average sound power levels were similar so the corresponding correction to obtain yearly averaged DNL and DENL is 1.9 dB (SD = 0.9 dB) higher than the modeled SPL in the CNHS.

The change from modeled levels to yearly average levels is 2.7 dB smaller than the correction found by van den Berg (2008) for two turbine models in the Netherlands. This means that for example, a modeled A-weighted level of 40 dB would be associated with a 41.9 dB long-term average DNL in the CNHS but a 44.7 dB long-term average DNL in the Netherlands. The calculations were repeated using the CNHS hub height wind speed data and the two wind turbine models used by van den Berg. The results showed that the main determinant of the 2.7 dB difference between the two studies was not the change in annual variation of wind speeds. Rather, the effect was largely determined by the difference in wind turbine sound power levels, as functions of wind speed.

D. Estimated C-weighted SPL based on extrapolation of manufacturer data using measurements

Overall, in the CNHS, for 8 m/s wind speed, the C-weighted WTN SPL, L_{eqC} can be related to the A-weighted SPL, L_{eqA} (for $L_{\mathrm{eqA}} > 25$ dB), using the formula

$$L_{\mathrm{eqC}} = 0.514 L_{\mathrm{eqA}} + 34.4, \quad (1)$$

where the SD is approximately 1.5 dB for $L_{\mathrm{eqA}} > 30$ dB. The linear correlation coefficient for this equation (Pearson's r) is 0.81. Given this one-to-one relationship between A and C weighted values there is no statistical advantage to using one metric over the other. Similar results have been obtained in other studies (Søndergaard, 2013; Pawlaczyk-Łuszczyńska *et al.*, 2014; Tachibana *et al.*, 2014). Nevertheless, this finding should not be interpreted to mean that reduction of A-weighted SPL can automatically be used as the only basis for noise mitigation measures aimed at reducing community reaction. If investigations show that this reaction can be reasonably demonstrated as being due to low frequency noise, mitigation measures should target noise metrics that most accurately reflect the frequencies of interest.

E. Ambient SPL in the absence of wind turbines

The AUC (2013) ambient noise predictions were broadly consistent with the available measurements. At 8 dwellings where the wall transmission loss was measured in the CNHS area, the corrected outdoor ambient noise measurements were lower than predicted values by 3.2 dB (SD = 4.5 dB). This

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difference is minor for a number of reasons: (i) 3 dB was subtracted from measurements to account for the facade reflection; (ii) the microphone was shielded from noise sources behind the dwelling; and (iii) measurements were not used in the analysis when there were local vehicle pass-bys, or other nearby noise sources present.

Figure 1 shows that ambient noise levels can exceed the wind turbine noise. In this figure most data were from nighttime, when AUC (2013) predicted noise levels were 40 dB A-weighted. In the 4 kHz band alone, the ambient noise in Fig. 1 was over 40 dB. As noted in Sec. III A, this is likely due to vegetation noise from trees and crops, which were common in the CNHS areas.

The ambient noise results suggest that, in the CNHS, the WTN was highest away from more densely populated areas and roads. The calculated ambient SPL in the CNHS spanned the range of AUC (2013) predictions. In addition to the 1232 dwellings where ambient noise was calculated using AUC (2013), there were six dwellings near the freeway where the calculated ambient SPL values were found to be up to 61 dB A-weighted (FHWA, 1998). Overall, beyond approximately 1 km from the wind turbines a typical average nighttime A-weighted ambient SPL of 44.9 dB was found, independent of the calculated WTN SPL (corresponding to 8 m/s wind speed). An exception occurred within approximately 1 km of the wind turbines for the 743 dwellings where calculated WTN SPL was above 35 dB A-weighted. At these locations the average calculated ambient SPL dropped 0.6 dB for every dB increase in calculated WTN SPL.

Of the 1238 dwellings in the CNHS, 471 dwellings (38.0%) were in areas below 300 persons per square mile. Comparison to the USEPA estimates based on population density (USEPA, 1974; Schomer *et al*., 2011) shows that Table I extends the results to lower population densities and gives values consistent with the available measurements (Schomer *et al*., 2011).

IV. CONCLUSIONS

The findings of this study provide the sound pressure levels needed for the determination of exposure response relationships from the CNHS.

The simplified Swedish noise propagation method was found to give results similar to that obtained using the ISO (1996) method. Although topographical corrections do not appear in the Swedish model, they were not important due to the flat topography in the CNHS areas. The similarity of results provides an added level of confidence in the findings reported in the CNHS.

Over distances less than 1 km, the SD for predicted outdoor SPL outside dwellings was 4 dB, but at 10 km this uncertainty was estimated to rise to at least 10 dB SD.

C-weighted levels were found to be approximately linearly related to the A-weighted levels. Given this one-to-one relationship between A- and C-weighted values there is no statistical advantage to using one metric over the other for WTN in the CNHS.

In comparing calculated long-term average exposure levels in different studies, it was found that it was important to consider the wind turbine sound power curves as a function of wind speed as well as the variation in the wind speed itself. For a long-term average SPL, the SPL based on 8 m/s wind speed should be reduced by 4.5 dB.

Background noise estimated from a Canadian model was consistent with the limited available measured data from the study and it showed that the wind turbines in the CNHS tended to be sited away from existing roads and densely populated areas.

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The authors have declared that no competing interests exist.

Attenborough, K., Taherzadeh, S., Bass, H. E., Di, X., Raspet, R., Becker, G. R., Güdesen, A., Chrestman, A., Daigle, G. A., L'Espérance, A., Gabillet, Y., Gilbert, K. E., Li, Y. L., White, M. J., Naz, P., Noble, J. M., and van Hoof, H. A. J. M. (**1995**). "Benchmark cases for outdoor sound propagation models," J. Acoust. Soc. Am. **97**(1), 173–191.

AUC (**2013**). Rule 012-Noise Control, Alberta Utilities Commission, available at http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx (Last accessed on 5/29/2014).

BC. (**2012**). Best practice for wind power project acoustic assessment British Columbia 2012, British Columbia Ministry of Forests, Lands and Natural Resource Operations, Ministry of Energy, Mines and Natural Gas Environmental Assessment Office, available at http://www2.gov.bc.ca/assets/gov/business/land-water-use/crown-land/bmp_wind_acoustic.pdf (Last accessed on 5/29/2014).

Blue Marble Geographics (**2014**). Global Mapper version 14, available at http://www.bluemarblegeo.com/products/global-mapper.php (Last accessed on 5/29/2014).

DataKustik GmbH® (**2014**). Cadna A version 4.4 Software for Immission Protection, available at www.datakustik.com (Last accessed on 5/29/2014).

DeGagne, D. C. (**1999**). "The evolution of environmental noise legislation for Alberta's energy industry over three decades," Can. Acoust. **27**(3), 76–77.

Eurasto, R. (**2006**). "Nord2000 for road traffic noise prediction. Weather classes and statistics," Research Report VTT-R-02530-06, VTT Technical Research Centre of Finland. http://vejdirektoratet.dk/DA/vejsektor/forskning-og-udvikling/Miljovenlige%20veje/Stoj/NORD2000/Documents/PDF%20til%20st%C3%B8jtema/image.pdf (Last accessed on 12/17/2014).

FHWA (**1998**). FHWA Traffic Noise Model®, technical manual (United States Department of Transportation, Federal Highway Administration, Washington, DC).

Forssén, J., Schiff, M., Pedersen, E., and Persson Waye, K. P. (**2010**). "Wind turbine noise propagation over flat ground: Measurements and predictions," Acta Acust. Acust. **96**(4), 753–760.

Gaudet, J. F., and Profitt, W. M. (**1958**). *Native Trees of Prince Edward Island* (Department of Agriculture, Charlottetown, Prince Edward Island).

GeoBase–Canadian Digital Elevation Data–1945–2010 (**2010a**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/browse.do?produit=cded&decoupage=50k&map=040J (Last accessed on 1/30/2014).

GeoBase–Land Cover, Circa 2000. 1996–2005 (**2005**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/browse.do?produit=csc2000v&decoupage=250k&map=040 (Last accessed on 2/19/2014).

GeoBase–National Railway Network (**2012**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/search.do?produit=nrwn&language=en (Last accessed on 1/20/2014).

GeoBase–National Road Network (**2010b**). Ministry of Natural Resources, Ottawa, ON, http://www.geobase.ca/geobase/en/search.do?produit=nrn&language=en (Last accessed on 12/23/2013).

Hubbard, H. H., and Shepherd, K. P. (**1991**). "Aeroacoustics of large wind turbines," J. Acoust. Soc. Am. **89**(6), 2495–2508.

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IEC (**2012**). IEC 61400-11 Ed. 3.0. "Wind turbine generator systems—Part II: Acoustic noise measurement techniques" (International Electrotechnical Commission, Geneva, Switzerland).
ISO (**1993**). ISO 9613-1—Acoustics. "Attenuation of sound during propagation outdoors. Part I: Calculation of the absorption of sound by the atmosphere" (International Organization for Standardization, Geneva, Switzerland).
ISO (**1996**). ISO 9613-2—Acoustics. "Attenuation of sound during propagation outdoors. Part 2: General method of calculation" (International Organization for Standardization, Geneva, Switzerland).
ISO (**1998**). ISO 140-5—Acoustics. "Measurement of sound insulation in buildings and of building elements-Part 5: Field measurements of airborne sound insulation of facade elements and façades" (International Organization for Standardization, Geneva, Switzerland).
ISO (**2007**). ISO 1996-2—Acoustics. "Description, assessment and measurement of environmental noise. Part 2: Determination of environmental noise levels" (International Organization for Standardization, Geneva, Switzerland).
Jonasson, H. (**2007**). "Determination of Lden and Lnight using measurements," SP Technical Research Institute of Sweden, report IMA32-040510 delivered to IMAGINE project.
Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., Broner, N., Richarz, W., and van den Berg, F. (**2016**). "Wind turbine sound power measurements," J. Acoust. Soc. Am. **139**(3), 1431–1435.
MG Acoustics. (**2014**). Analysis, modeling, and prediction of infrasound and low frequency noise from wind turbine installation, phase 1: PEI site, final report, MG Acoustics report for Health Canada, 81 pp.
Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., Denning, A., McGuire, D., Bower, T., Lavigne, E., Murray, B. J., Weiss, S. K., and van den Berg, F. (**2016**). "Exposure to wind turbine noise: Perceptual responses and reported health effects," J. Acoust. Soc. Am. **139**(3), 1443–1454.
Öhlund, O., and Larsson, C. (**2015**). "Meteorological effects on wind turbine sound propagation," Appl. Acoust. **89**, 34–41.
ONMOE (**2008**). Noise guidelines for wind farms—interpretation for applying MOE NPC publications to wind power generating facilities—October, PIBS 4709e, Ontario Ministry of the Environment.
ONMOE (**2011**). Compliance protocol for wind turbine noise—guideline for acoustic assessment and measurement, PIBS 8540e, Ontario Ministry of the Environment.
ONMT (**2010**). Provincial Highways Traffic Volumes 2010, Highway Standards Branch, Traffic Office, Ontario Ministry of Transportation.
ONMT. (**2013**). icorridor Ontario Ministry of Transportation http://www.mto.gov.on.ca/iCorridor/map.shtml?accepted=true#tab_4 (Last accessed on 12/23/2013).
Ontario Highway Traffic Act (**2011**). Revised Statutes of Ontario 1990, Revised Regulations of Ontario 1990, Regulation 587: Equipment https://www.ontario.ca/laws/regulation/900587 (Last accessed on 2/19/2016).
Ontario Ministry of Natural Resources (**2014**). The Tree Atlas. http://www.ontario.ca/environment-and-energy/tree-atlas (Last accessed on 11/12/14).
Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., and Waszkowska, M. (**2014**). "Evaluation of annoyance from the wind turbine noise: A pilot study," Int. J. Occup. Environ. Health **27**, 364–388.
Pedersen, E. (**2007**). "Human response to wind turbine noise—perception, annoyance and moderating factors," Doctoral thesis, Göteborg University, Sweden.
Pedersen, E., and Halmstad, H. I. (**2003**). "Noise annoyance from wind turbines: A review," Report 5308, Naturvårdsverket, Swedish Environmental Protection Agency pp. 1–26.
Pedersen, E., and Persson Waye, K. (**2004**). "Perception and annoyance due to wind turbine noise—A dose-response relationship," J. Acoust. Soc. Am. **116**(6), 3460–3470.
Pedersen, E., van den Berg, F., Bakker, R., and Bouma, J. (**2009**). "Response to noise from modern wind farms in The Netherlands," J. Acoust. Soc. Am. **126**(2),634–643.
PEIMT (**2012**). Traffic volume for Prince Edward Island 2012, Capital Projects, Engineering Services, Prince Edward Island Ministry of Transportation and Infrastructure Renewal, available upon request at http://www.gov.pe.ca/tir/index.php3?number=1001593.
Plovsing, B., and Søndergaard, B. (**2011**). "Wind turbine noise propagation: Comparison of measurements and predictions by a method based on geometrical ray theory," Noise Control Eng. J. **59**(1), 10–22.
Schomer, P., Freytag, J., Machesky, A., Luo, C., Dossin, C., Nookala, N., and Pamdighantamc, A. (**2011**). "A re-analysis of Day-Night Sound Level (DNL) as a function of population density in the United States," Noise Control Eng. J. **59**(3), 290–301.
SEPA (**2001**). "Ljud från vindkraftverk" ("Noise from wind turbines"), Report 6241 (in Swedish), Swedish Environmental Protection Agency, Stockholm.
SEPA (**2012**). "Ljud från vindkraftverk" ("Noise from wind turbines"), Report 6241 version 3.0 (in Swedish), Swedish Environmental Protection Agency, Stockholm.
Sharma, M., and Parton, J. (**2007**). "Height-diameter equations for boreal tree species in Ontario using a mixed effects modeling approach," For. Ecol. Manage. **249**, 187–198.
Søndergaard, B. (**2013**). "Low frequency noise from wind turbines: Do the Danish regulations have any impact?," *Wind Turbine Noise 2013*, 28–30 August 2013, Denver, CO.
Statistics Canada (**2011**). Highlights and analysis, 2011 Census of Agriculture, available at http://www.statcan.gc.ca/eng/ca2011/ha (Last accessed on 10/7/2015).
Statistics Canada (**2012**). Census Profile, 2011 Census of Population, Statistics Canada Catalogue no. 98-316-XWE, Ottawa, released October 24, 2012, http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E.
Sutherland, L. C., and Bass, H. E. (**2004**). "Atmospheric absorption in the atmosphere up to 160 km," J. Acoust. Soc. Am. **115**(3), 1012–1032.
Sutherland, L. C., and Bass, H. E. (**2006**). "Erratum: Atmospheric absorption in the atmosphere up to 160 km," J. Acoust. Soc. Am. **120**(5), 2985.
Tachibana, H., Yano, H., Fukushima, A., and Shinichi, S. (**2014**). "Nationwide field measurement of wind turbine noise in Japan," Noise Control Eng. J. **62**(2), 90–101.
USEPA (**1974**). "Population Distribution of the United States as a Function of Outdoor Noise Level," Report EPA 550/9-74-009 (U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Washington, DC).
van den Berg, F. (**2008**). "Criteria for wind farm noise: Lmax and Lden," *EURONOISE 2008*, June 29–July 4, Paris, pp. 4043–4048.
van den Berg, G. P. (**2004**). "Effects of the wind profile at night on wind turbine sound," J. Sound Vib. **277**(4-5), 955–970.
Van Renterghem, T., Bockstael, A., De Weirt, V., and Botteldooren, D. (**2013**). "Annoyance, detection and recognition of wind turbine noise," Sci. Total Environ. **456–457**, 333–345.
Willshire, W. L., and Zorumski, W. E. (**1987**). "Low-frequency acoustic propagation in high winds," in *Noise-Con87, Proceedings of the National Conference on Noise Control*, Engineering, State College, PA, June 8–10, pp. 275–280.

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